Spatial Coherence of Nonlinear, Nonstationary, Non-gaussian Ocean Waves On a One-mile Scale from Scanning Radar Altimeter Data

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INTRODUCTION

This report is complementary to the report of the same title submitted by Borgman and Marrs (Contract No. N00014-98-C-0206) and both relate to the joint proposal of the same title by Borgman, Walsh, and Marrs. The Borgman and Marrs report describes progress on the principal study, using data from the NASA/GSFC Scanning Radar Altimeter (SRA) (Walsh et al., 1989, 1996) to investigate properties of waves in the open ocean related to Mobile Offshore Base (MOB) concerns. That report covers all areas (Long-Term Goal, Objectives, Approach, Impact/Application, Transitions and Related Projects, etc.) of the principal study and they will not be repeated here. This report describes work underway to assess the accuracy of the data being used in the principal study by estimating tilt modulation distortions in the wave topography measured by a scanning radar altimeter.

The SRA two-way beamwidth of approximately 1^{o} would produce a half-power footprint at nadir of 17.5 m from 1 km height. This is the nominal aircraft height for the high altitude SRA data from the Southern Ocean Waves Experiment (SOWEX) used in the principal study. At the nominal edge of the SRA swath, the cross-track dimension of the footprint increases to 20.3 m because the beam intercepts the sea surface at a 22^{o} incidence angle. It would be expected that spatial filtering by the footprint would reduce the apparent amplitude of shorter ocean wavelengths. But we will see that modulation of the radar cross section caused by the tilts of the waves can actually make short waves appear much higher in amplitude at off-nadir locations.

APPROACH

The SRA and its predecessor, the Surface Contour Radar (SCR), typically acquired data while flying in the downwind or upwind directions because that produced the best directional wave spectra. However, a recent examination of SRA data acquired on October 17, 1994, suggested that wave tilt modulation of the radar cross section might affect the SRA elevation measurements. The aircraft was at 520 m altitude flying parallel to the beach at Duck, NC, with the SRA scanning perpendicular to the crests of incoming swell. The apparent wave height increased significantly from nadir to the edge of the swath.

To quantify this effect, a two-dimensional simulation has been performed in the cross-track plane only

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which assumed that sinusoidal waves of constant wavelength propagate in the cross-track direction (and are infinitely long-crested in the along-track direction).

WORK COMPLETED

A nominal Gaussian antenna pattern of 1° half-power width was represented by 60 points spaced at 0.05° intervals between -1.5° and 1.5° relative to the antenna boresight. The variation of backscattered power with local incidence angle was computed from values of sea surface mean square slope (mss) selected to represent nearly omnidirectional scattering (an unrealistic condition) and a variety of wind speeds at the SRA 36 GHz operating frequency. The antenna incidence angle boresight was varied from nadir to 24° off-nadir, which could occur at 2° aircraft roll attitude, in 2° increments.

At each cross-track position determined by the nominal boresight off-nadir angle, the phase of sinusoidal waves of 400, 200, 100, 75, and 50 m wavelength were varied from 0° to 355° in 5° increments. For each phase of each wavelength, the range to the centroid of the backscattered power was computed using the variation in antenna gain times the variation of the radar cross section with local incidence angle determined by the combination of off-nadir angle and the sea surface tilt caused by the wave. That range was ascribed to the nominal boresight of the antenna and the surface elevation was computed from the expression $e = h - r \cos \theta$, where e is the output elevation from the SRA, h is the aircraft height, r is the computed centroid range, and θ is the nominal boresight angle.

RESULTS

Figure 1 shows the results using a mss of 10. This is absurdly large considering that the Plant (1982) upper limit on mss is 0.08, but it is a convenient way computationally to look at nearly omnidirectional scattering for which there would be no tilt modulation.

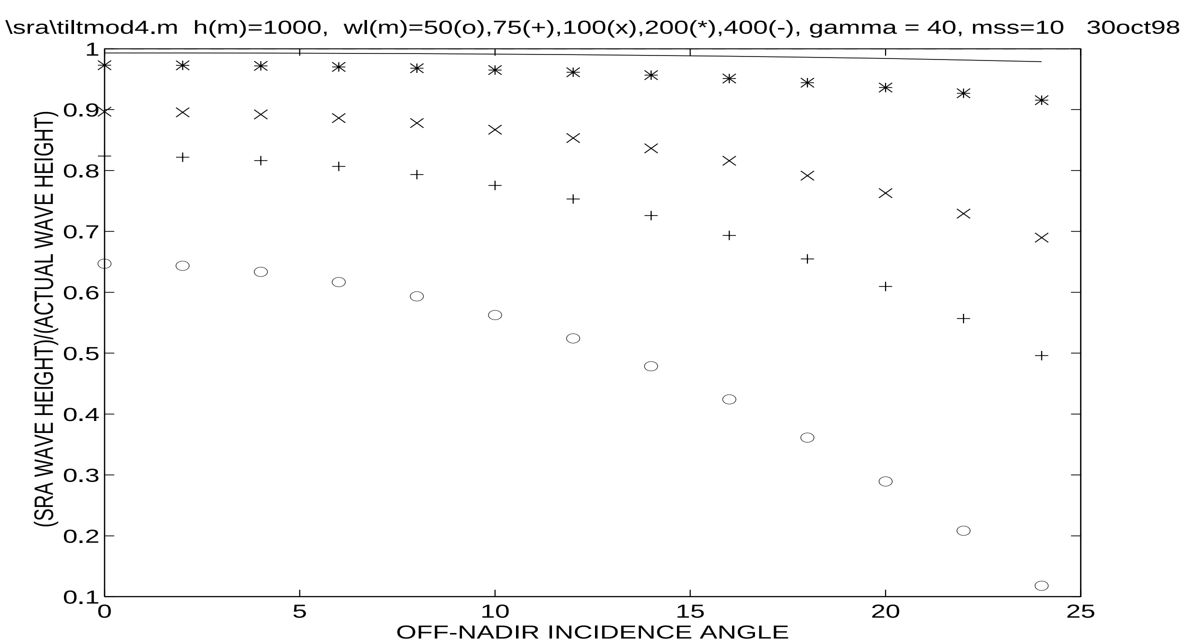

Figure 1. Antenna footprint spatial filtering effects for nearly omnidirectional scattering.

Figure 1 shows the simulation computed ratio of the wave height observed that would be observed by the SRA to the actual wave height for five wavelengths: 400, 200, 100, 75, and 50 m. The parameter gamma in the figure header is taken to be the ratio of wavelength to wave height. A value of 40 would be representative of a fully-developed sea, while 20 would indicate a developing sea and 80 would be swell. All three values were used, but only the fully-developed case results are shown here.

At 1 km height, the SRA swath width is 800 m, so the five wavelengths correspond to a swath which is 2, 4, 8, 10.7, or 16 wavelengths wide. The results of the simulation do not change with aircraft height as long as the corresponding wavelength is changed to maintain the same swath width to wavelength ratio, and gamma is also held constant.

Figure 1 shows the mss = 10 case for which the scattering is nearly omnidirectional. In this case the measured wave height is less than the actual wave height due to spatial filtering by the antenna footprint. The solid curve shows that if the swath is only two waves wide (400 m wavelength case), then the reduction of the apparent wave height is only 1% or 2%. For four waves across the swath (200 m wavelength case) the reduction is about 3% at nadir and about 8% at 24° off-nadir. As would be expected, the spatial filtering become more severe as the wavelength shortens, bringing it closer to the size of the antenna footprint. For 50 m wavelength (16 waves across the swath) the reduction in apparent wave height at nadir is about 35% and at 24° off-nadir it is almost 90%.

Figure 2 shows that when the highest reasonable value of mss is used in the simulation (the Plant limit of 0.08), the nadir values of the wave height ratio are the same as for the omnidirectional scattering case. But something quite surprising is observed as the off-nadir angle increases. The apparent wave height increases and becomes larger than the actual wave height by about 10° off-nadir. And the shorter the wavelength, the larger the apparent wave height increase. This represents a systematic over-estimate of the wave amplitude for waves propagating in the cross-track direction.

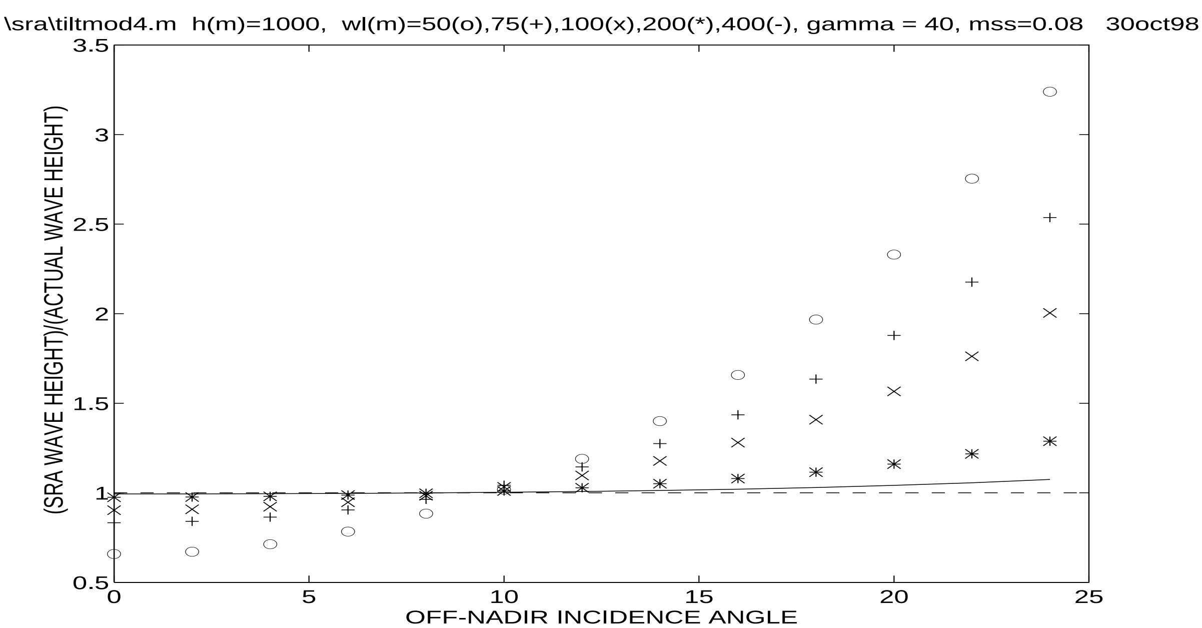

Figure 2. Tilt modulation effects for mss corresponding to the Plant (1982) upper limit on mss of 0.08.

For lower values of mss the situation worsens. Figures 3 and 4 show the simulation results for mss values of 0.04 and 0.02, which correspond to wind speeds of about 12 m/s and 4 m/s, respectively. At the low wind speed, even the 200 m wavelength sinusoid has an apparent wave height that is more than a factor of two too large at the edge of the swath.

When the aircraft is flying perpendicular to the wave crests, the slopes in the cross-track plane of incidence as relative small because the SRA is scanning parallel to the wave crests. This was the situation for most of the high altitude (1 km) data taken during the Southern Ocean Waves Experiment (SOWEX) presently be analyzed under Contract No. N00014-98-C-0206 (Borgman et al., 1998). But tilt modulation effects are of great concern for SRA data collected this season on one of the NOAA hurricane hunter aircraft. The minimum aircraft altitude was 1.5 km and it frequently flew higher. For a given wavelength and gamma, the effect increases with increasing aircraft altitude. SRA raw data acquired at 1.5 km height in Hurricane Bonnie can be viewed at http://aol11.wff.nasa.gov/sra/bonnie-index.html. The image is quite impressive and shows the general variation of the wave field in the various quadrants, but it indicates that the SRA was scanning more nearly perpendicular to the wave crests than parallel to them most of the time because of the flight pattern used by NOAA for eye penetrations. These data need careful analysis before any quantitative conclusions can be drawn.

This analysis is still at an early stage and the results of the 2-dimensional simulation should not be viewed with too great alarm since the raw SRA data do not look absurd. But it was recognized during hurricane flights this year that the higher waves were predominately observed near the edge of the SRA swath. A 3-dimensional simulation is being developed to model waves propagating at various azimuthal angles relative to the cross-track plane. The results of this model will be verified by comparing them with SRA data and optimum correction procedures will be developed.

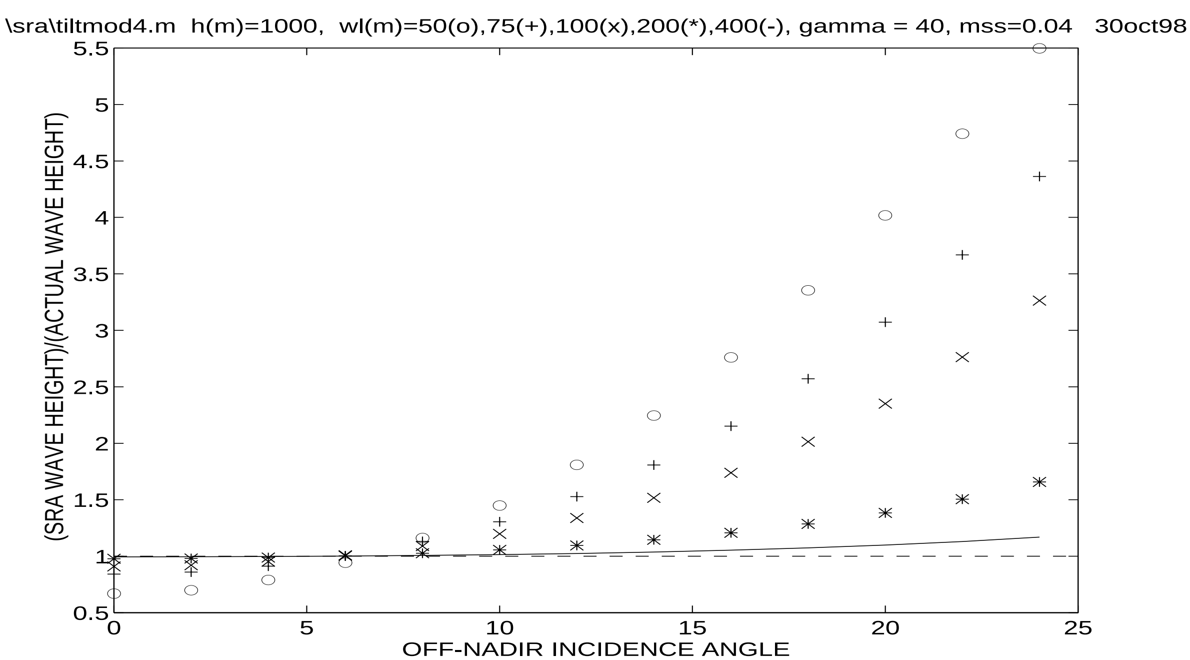

Figure 3. Tilt modulation effects for mss = 0.04, corresponding to a wind speed of about 12 m/s.

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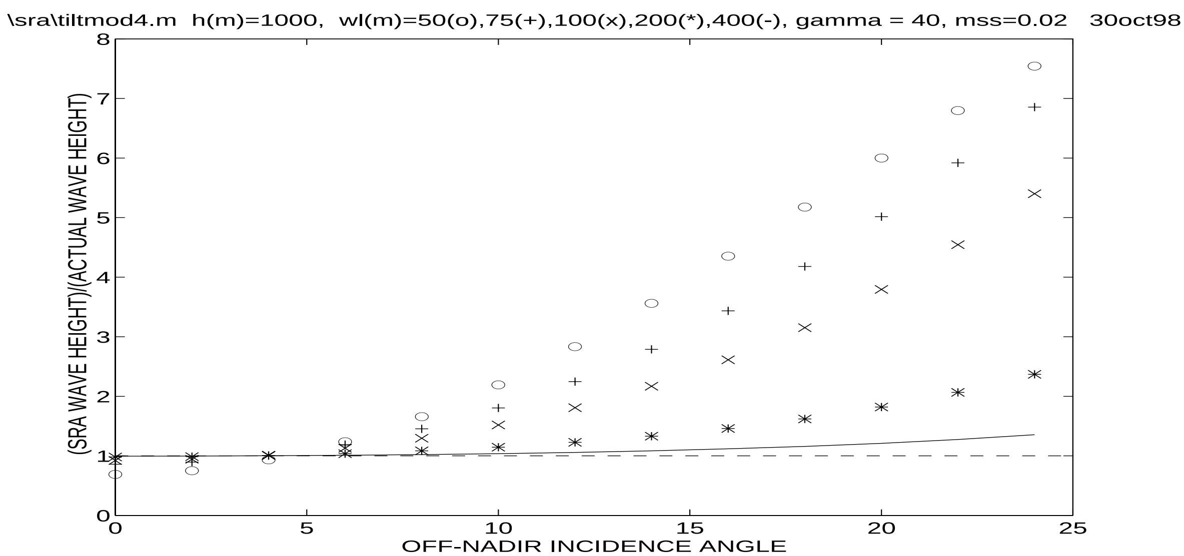

Figure 4. Tilt modulation effects for mss = 0.02, corresponding to a wind speed of about 4 m/s.